US009045994B2

(12) **United States Patent**
Bidkar et al.

(10) **Patent No.: US 9,045,994 B2**
(45) **Date of Patent: Jun. 2, 2015**

(54) **FILM RIDING AERODYNAMIC SEALS FOR ROTARY MACHINES**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 85 days.

(21) Appl. No.: **13/665,431**

(22) Filed: **Oct. 31, 2012**

(65) **Prior Publication Data**

US 2014/0119912 A1 May 1, 2014

(51) **Int. Cl.**

F16J 15/447	(2006.01)
F01D 11/02	(2006.01)
F16J 15/44	(2006.01)

(52) **U.S. Cl.**

CPC ***F01D 11/02*** (2013.01); *Y10T 29/49826* (2013.01); ***F01D 11/025*** (2013.01); ***F16J 15/442*** (2013.01); *F05D 2240/55* (2013.01)

(58) **Field of Classification Search**

USPC 277/411, 412, 413, 416, 500, 543, 545, 277/546, 578; 415/115, 138

See application file for complete search history.

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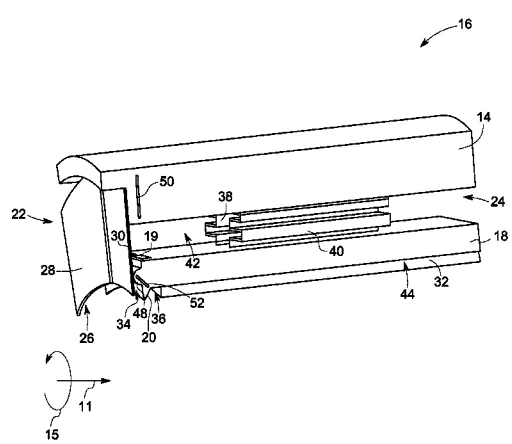
(57) **ABSTRACT**

A seal assembly for a rotary machine is provided. The seal assembly includes multiple sealing device segments disposed circumferentially intermediate to a stationary housing and a rotor. Each of the sealing device segments includes a stator interface element. The sealing device segment also includes a shoe plate having one or more labyrinth teeth facing the rotor and a load-bearing surface region, wherein the shoe plate allows a high pressure fluid to an upstream portion of the forwardmost labyrinth tooth and a low pressure fluid to a downstream portion of the aftmost labyrinth tooth. The sealing device segment further includes a secondary seal in contact with the stator interface element at a radially outer end and in contact with an elevated nose of the shoe plate on a radially inner end; and multiple bellow springs or flexures attached to the shoe plate and to the stator interface element.

22 Claims, 12 Drawing Sheets



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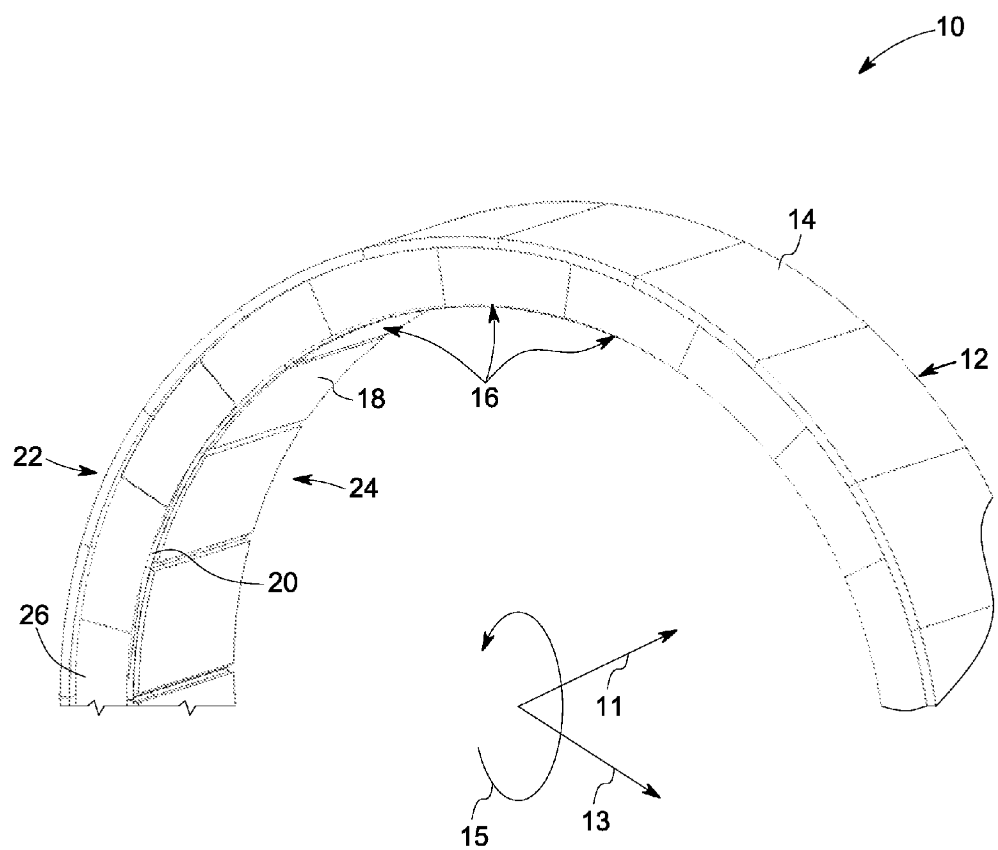

FIG. 1

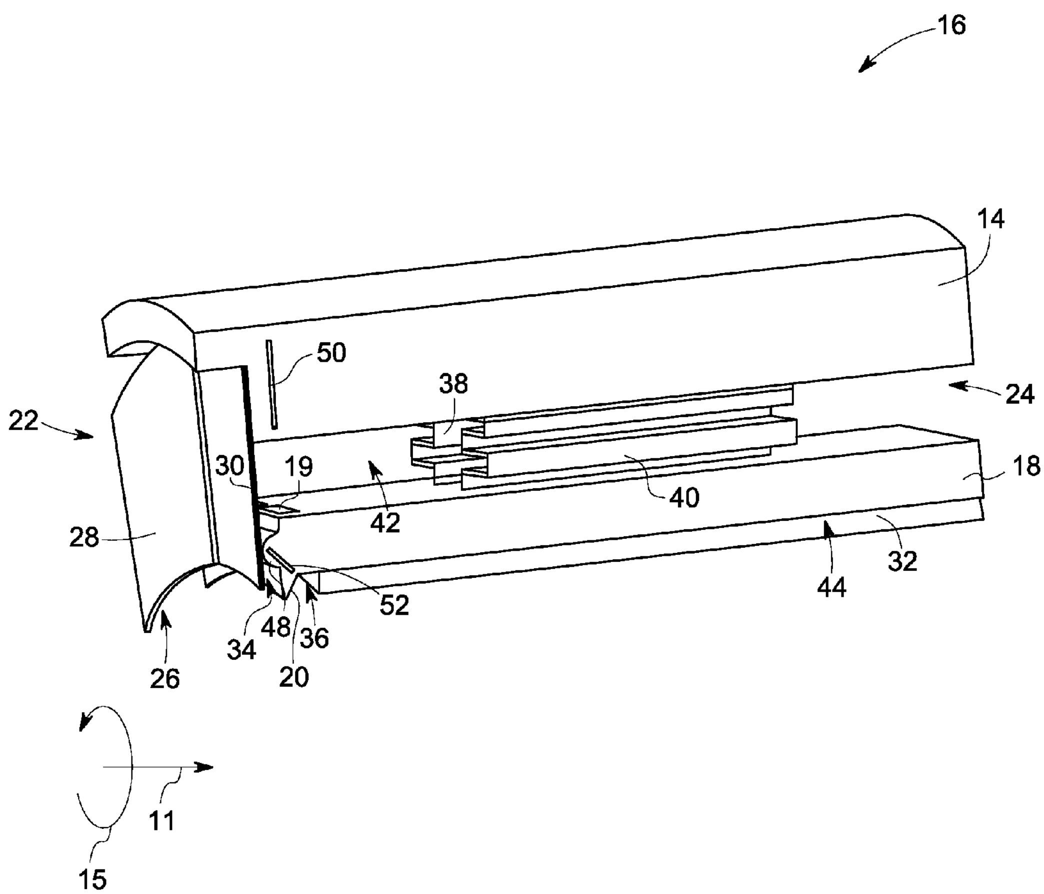

FIG. 2

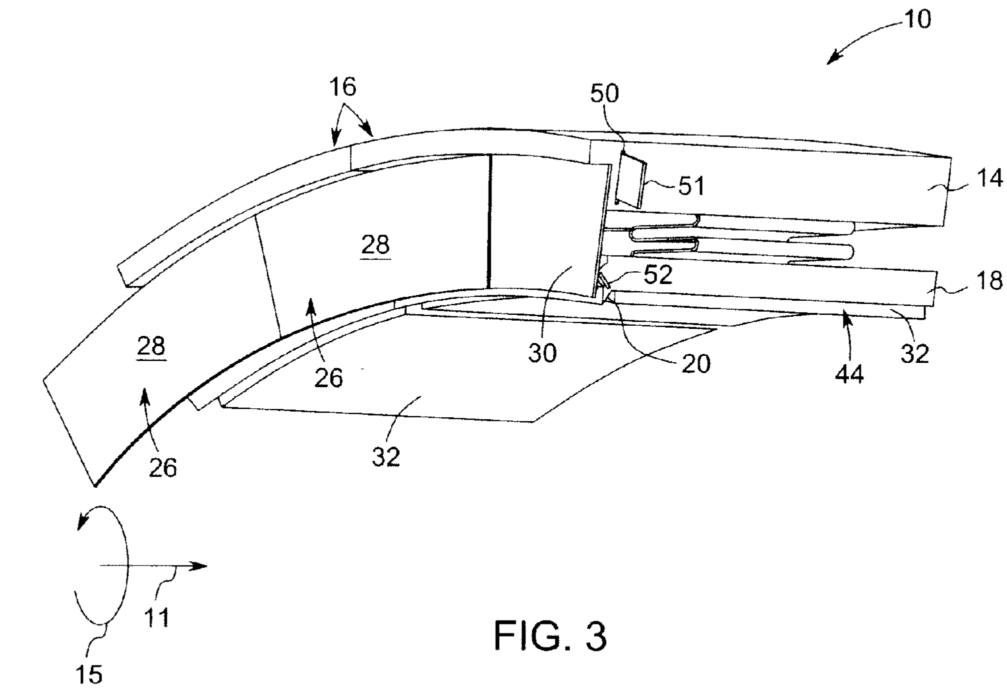
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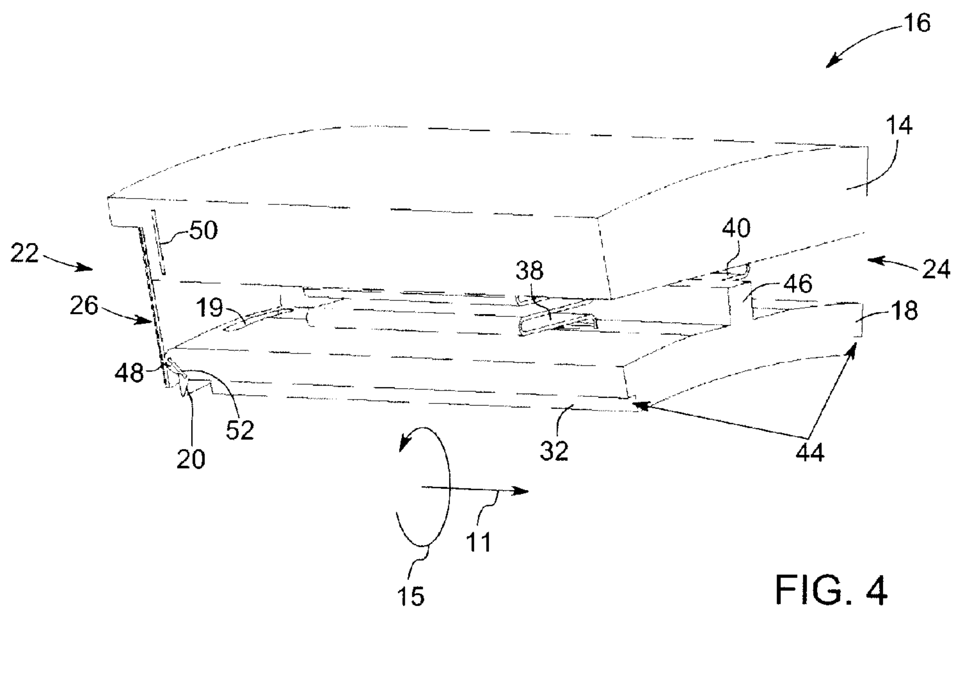
FIG. 3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11
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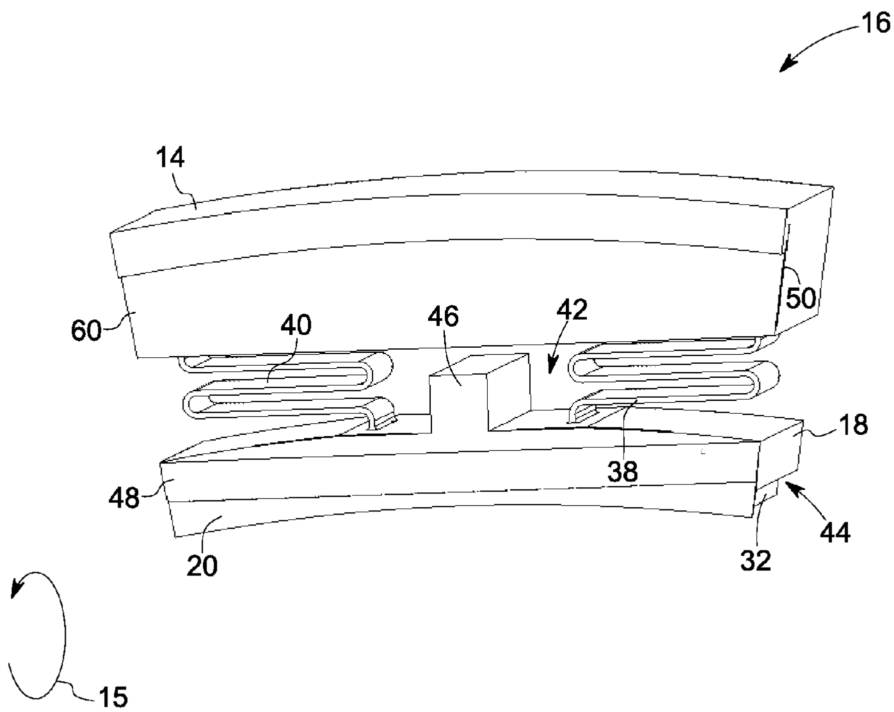
FIG. 4


16
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42
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48
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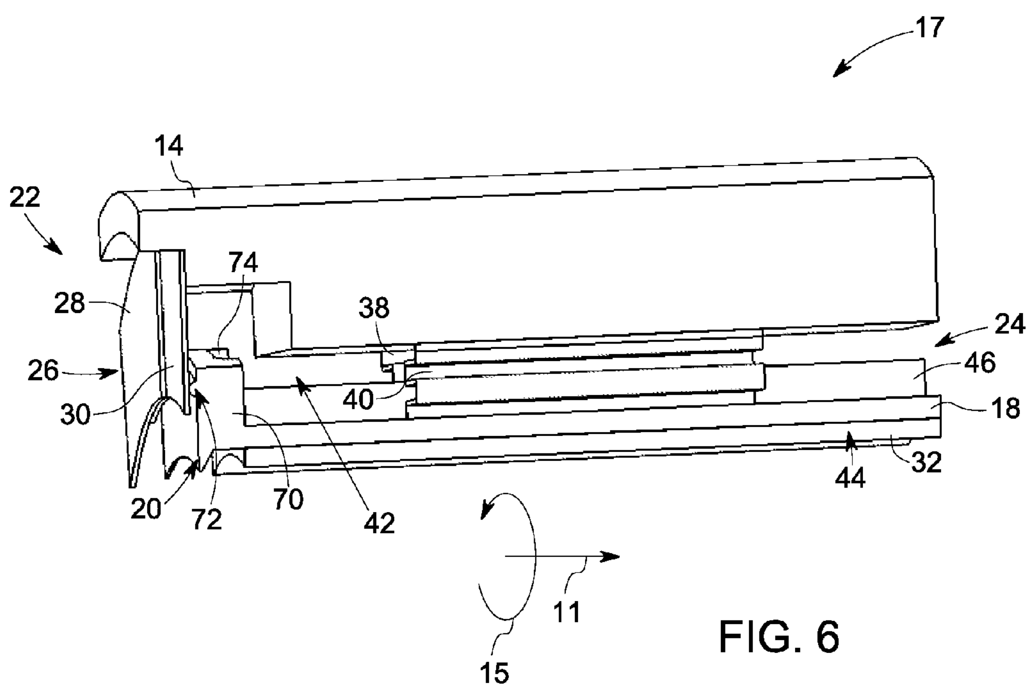
FIG. 5


17
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72
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FIG. 6

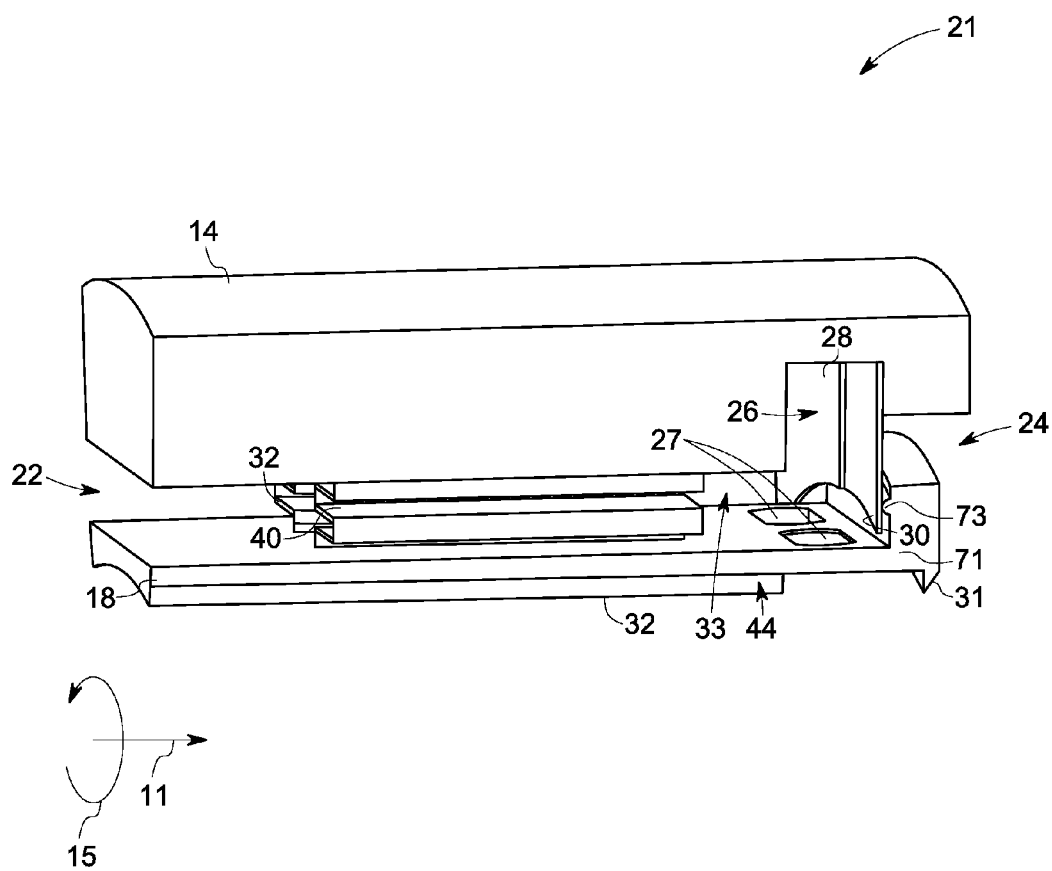

FIG. 7

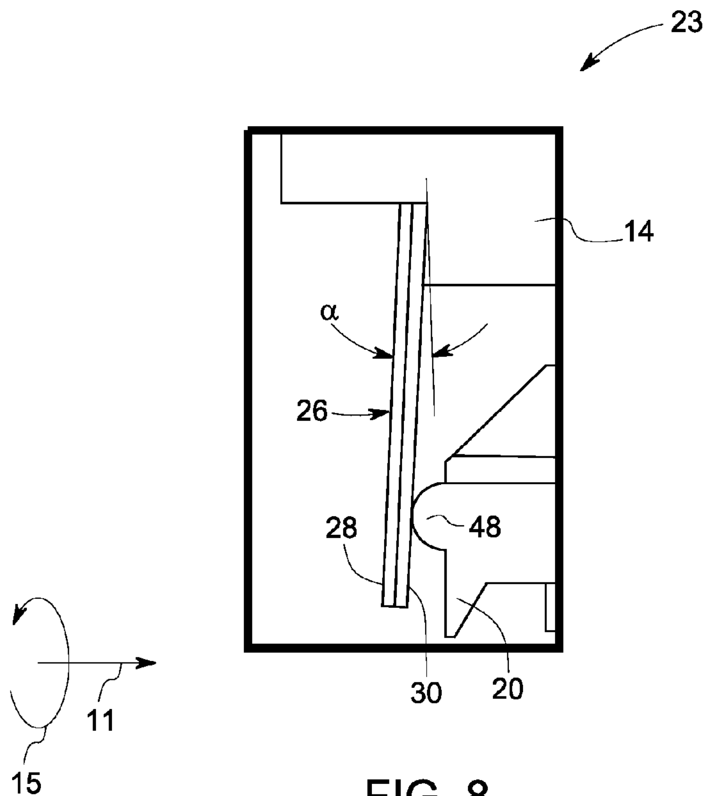

FIG. 8

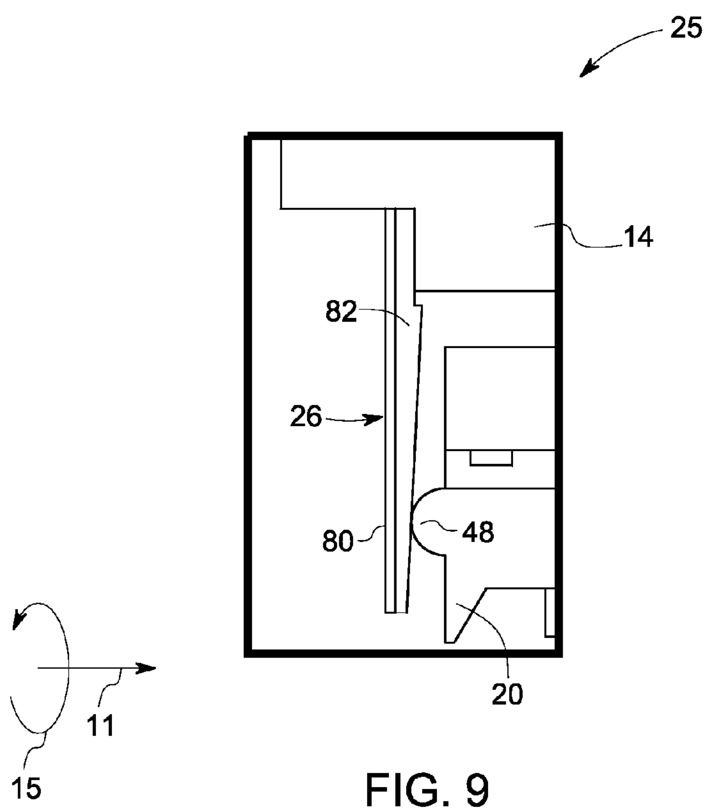

FIG. 9

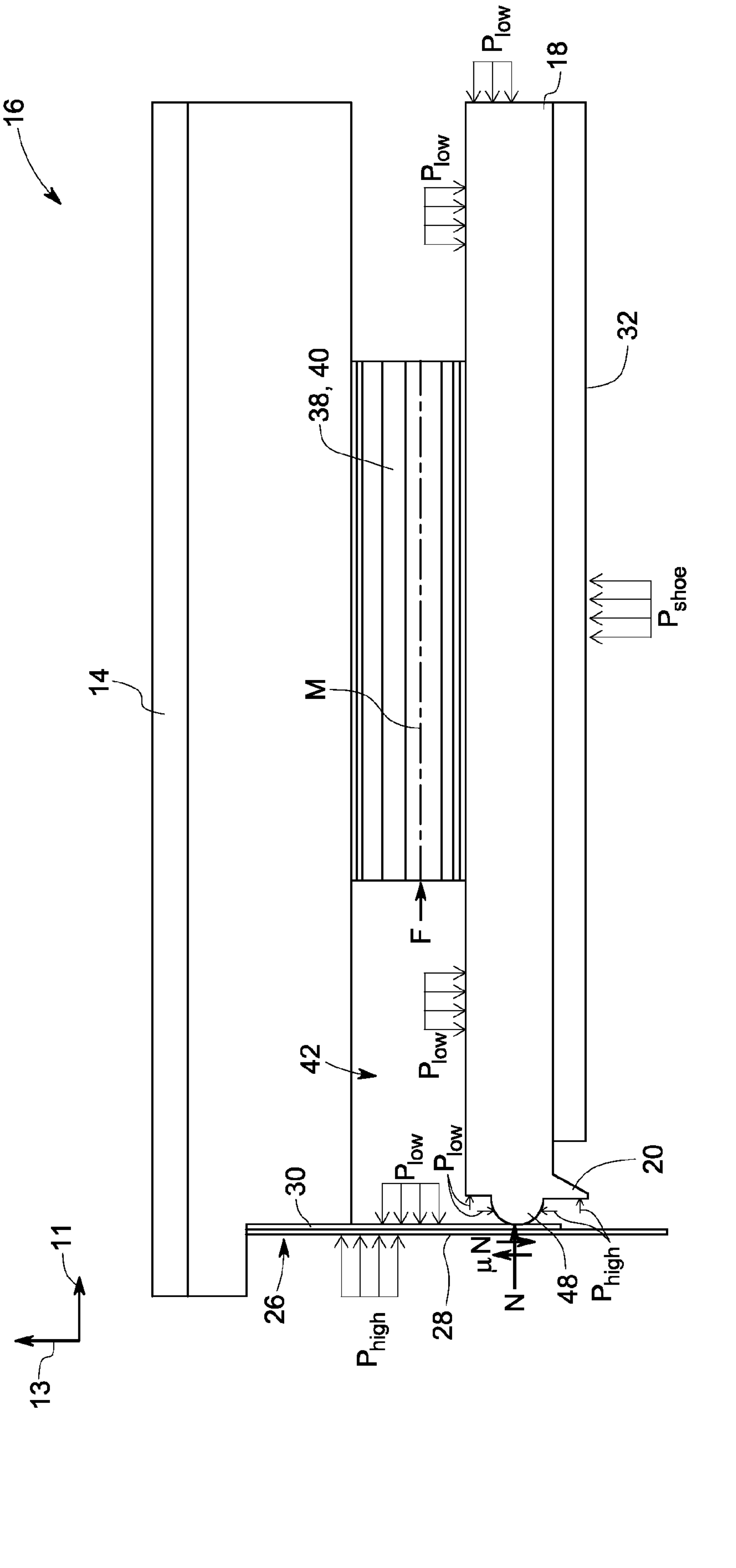

FIG. 10

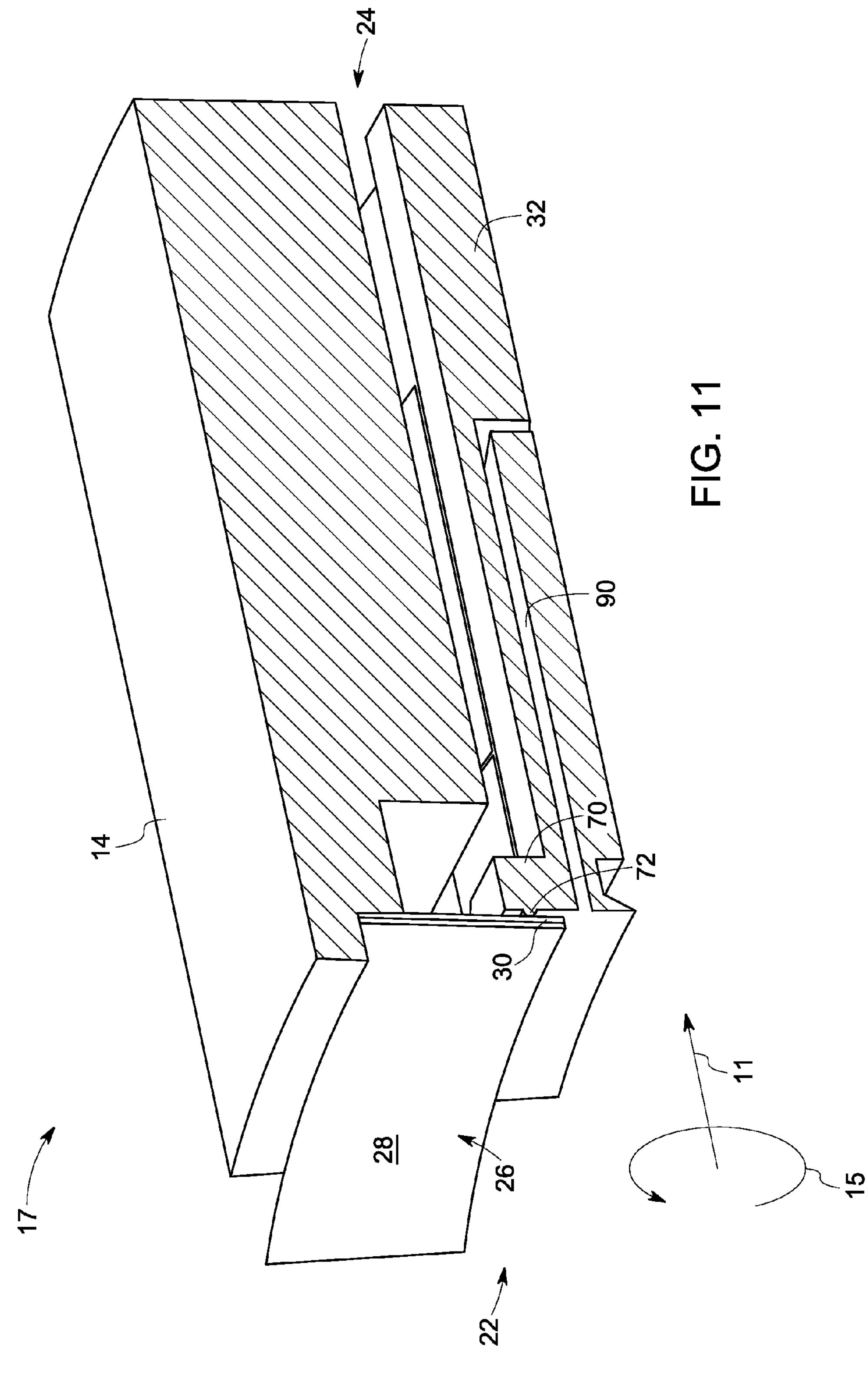

FIG. 11

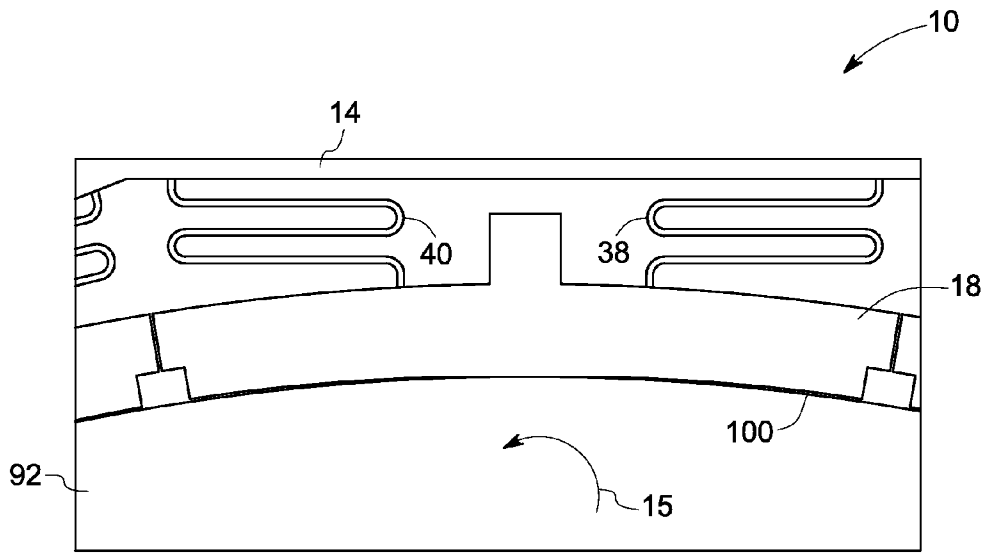

FIG. 12

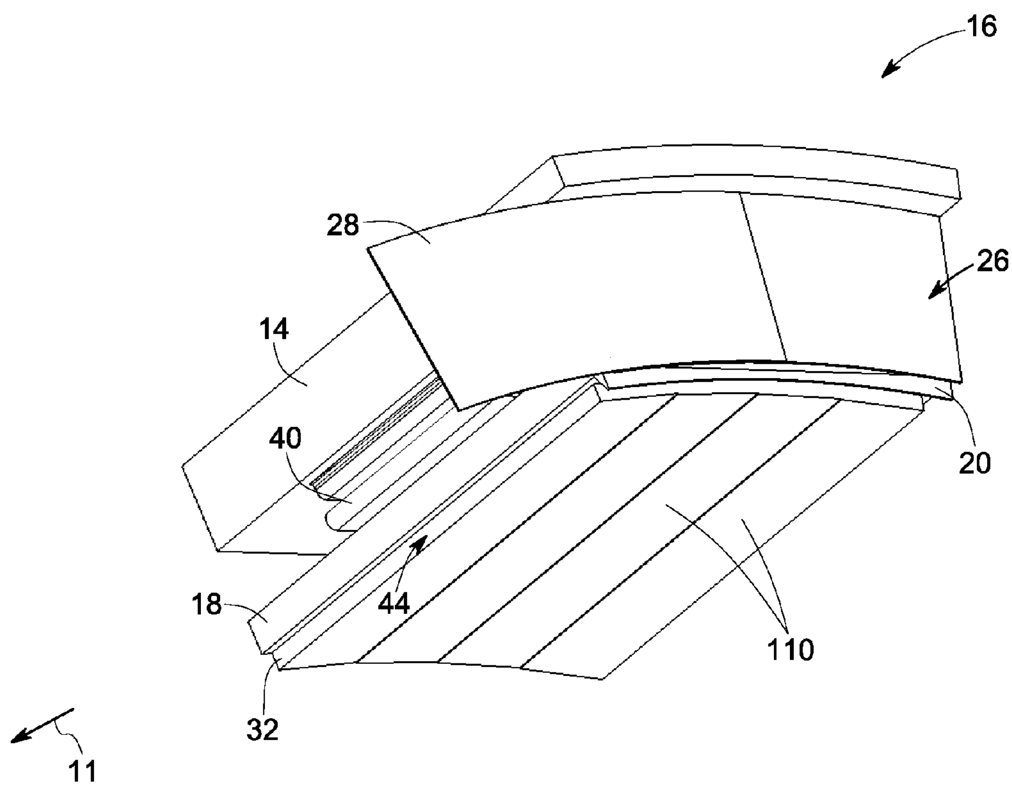

FIG. 13

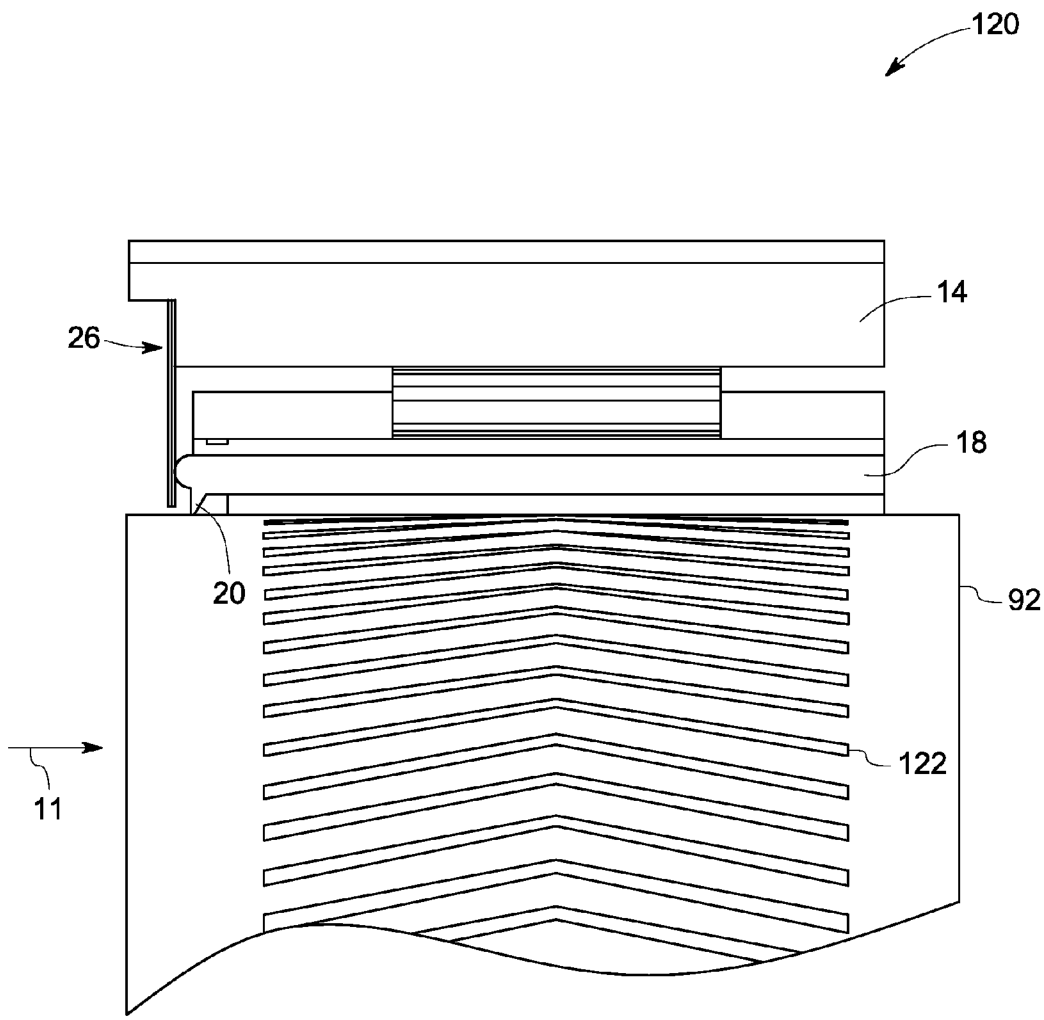

FIG. 14

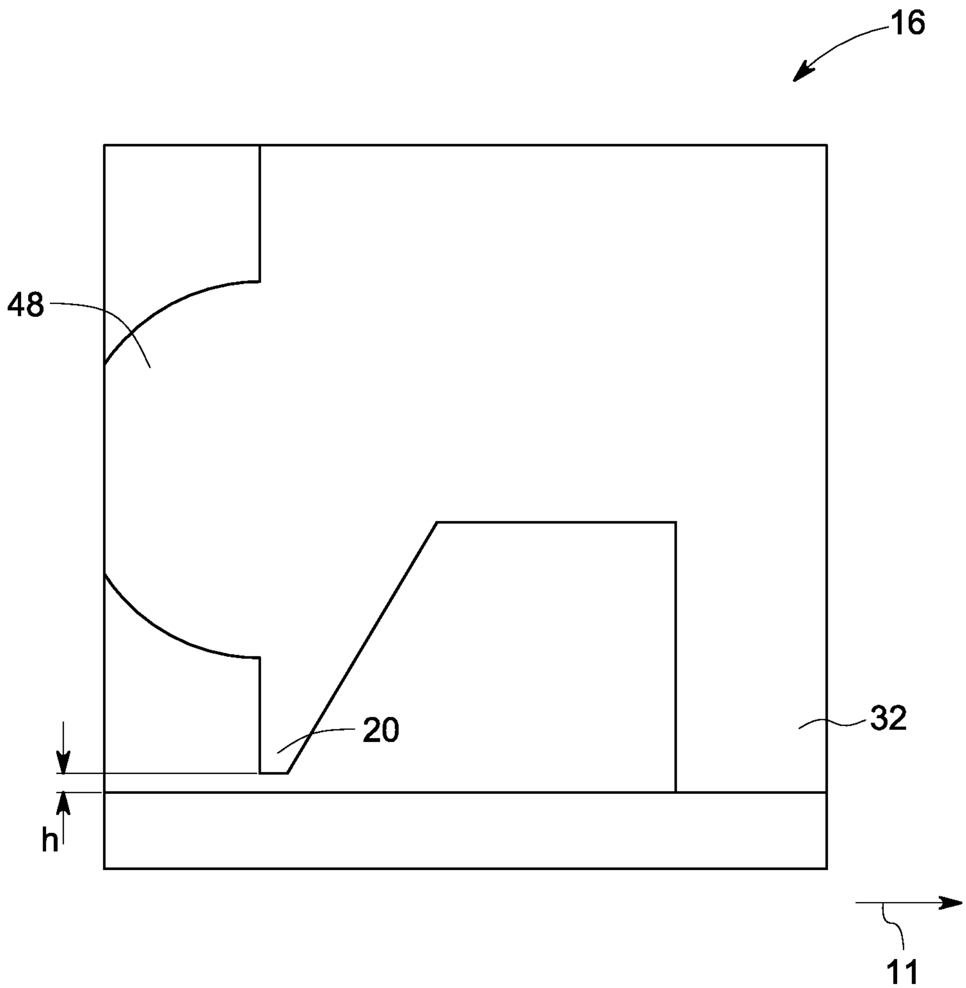

FIG. 15

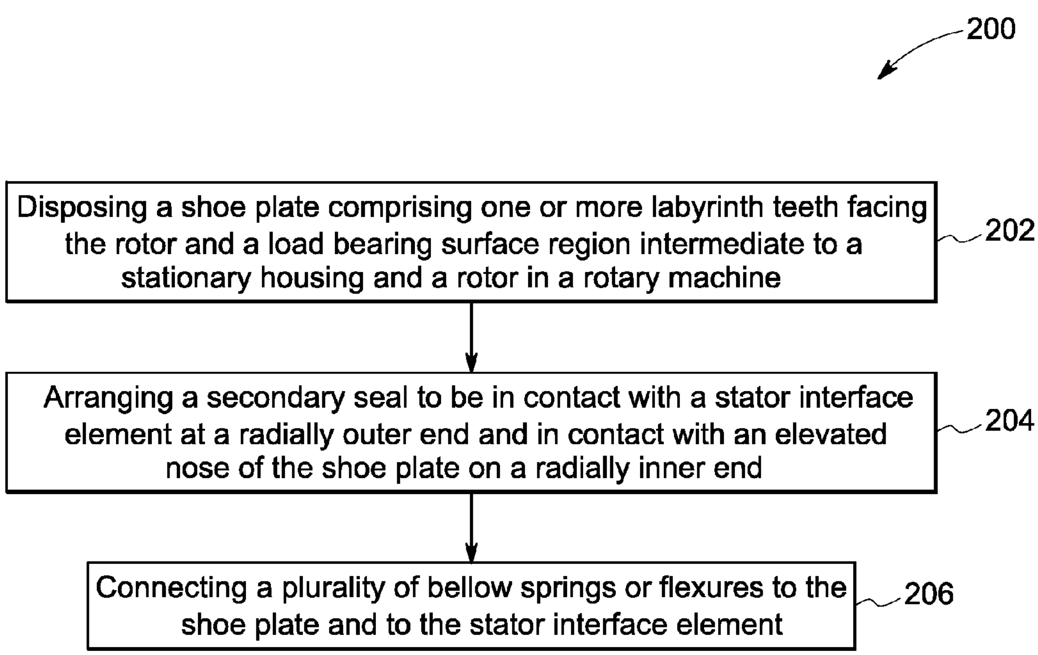
200
Disposing a shoe plate comprising one or more labyrinth teeth facing the rotor and a load bearing surface region intermediate to a stationary housing and a rotor in a rotary machine
202
Arranging a secondary seal to be in contact with a stator interface element at a radially outer end and in contact with an elevated nose of the shoe plate on a radially inner end
204
Connecting a plurality of bellow springs or flexures to the shoe plate and to the stator interface element
206

FIG. 16

FILM RIDING AERODYNAMIC SEALS FOR ROTARY MACHINES

BACKGROUND

The present application relates generally to seal assemblies for turbo-machinery and more particularly relates to film riding seal assemblies for sealing rotor-stator gaps and the like.

Various types of turbo-machinery, such as gas turbine engines, aircraft engines and steam turbines are known and widely used for power generation, propulsion, and the like. The efficiency of the turbo-machinery depends in part upon the clearances between the internal components and the leakage of primary and secondary fluids through these clearances. For example, large clearances may be intentionally allowed at certain rotor-stator interfaces to accommodate large, thermally or mechanically-induced, relative motions. Leakage of fluid through these gaps from regions of high pressure to regions of low pressure may result in poor efficiency for the turbo-machinery. Such leakage may impact efficiency in that the leaked fluids fail to perform useful work.

Different types of sealing systems are used to minimize the leakage of fluid flowing through turbo-machinery. The sealing systems, however, often are subject to relatively high temperatures, thermal gradients, and thermal and mechanical expansion and contraction during various operational stages that may increase or decrease the clearance therethrough. For example, traditional labyrinth seals that are assembled to run very tight clearance during start-up transient phase might run with large clearances during steady state operations, thereby leading to poor performance at steady state operation.

There is therefore a desire for improved compliant sealing assemblies for use with turbo-machinery for sealing rotor-stator gaps. Preferably such compliant sealing assemblies may provide tighter sealing during steady state operations while avoiding rubbing, wear caused by contact and damage during transient operations. Such sealing assemblies should improve overall system efficiency while being inexpensive to fabricate and providing an increased life for the associated parts.

BRIEF DESCRIPTION

In accordance with an embodiment of the invention, a seal assembly for a rotary machine is provided. The seal assembly includes multiple sealing device segments disposed circumferentially intermediate to a stationary housing and a rotor. Each of the sealing device segments includes a stator interface element. The sealing device segment also includes a shoe plate having one or more labyrinth teeth facing the rotor and a load-bearing surface region, wherein the shoe plate is configured to allow a high pressure fluid to an upstream portion of the forwardmost labyrinth tooth and a low pressure fluid to a downstream portion of the aftmost labyrinth tooth and further configured to generate an aerodynamic force between the shoe plate and the rotor. The sealing device segment further includes a secondary seal configured to be in contact with the stator interface element at a radially outer end and configured to be in contact with an elevated nose of the shoe plate on a radially inner end; and a plurality of bellow springs or flexures connected to the shoe plate and to the stator interface element.

In accordance with an embodiment of the invention, a method of manufacturing a sealing device segment is provided. The method includes disposing a shoe plate comprising one or more labyrinth teeth facing the rotor and a load-bearing surface region intermediate to a stationary housing and a rotor in a rotary machine, wherein the shoe plate is configured to allow a high pressure fluid to an upstream portion of the forwardmost labyrinth tooth and a low pressure fluid to a downstream portion of the aftmost labyrinth tooth and further configured to generate an aerodynamic force between the shoe plate and the rotor. The method also includes arranging a secondary seal to be in contact with a stator interface element at a radially outer end and in contact with an elevated nose of the shoe plate on a radially inner end. Further, the method includes connecting a plurality of bellow springs or flexures to the shoe plate and to the stator interface element.

In accordance with an embodiment of the invention, a rotary machine is provided. The rotary machine includes a rotor, a stator housing and multiple sealing device segments disposed circumferentially intermediate to the stationary housing and the rotor, wherein each of the segments comprises a stator interface element and a shoe plate comprising one or more labyrinth teeth facing the rotor and a load-bearing surface region, wherein the shoe plate is configured to allow a high pressure fluid to an upstream portion of the forwardmost labyrinth tooth and a low pressure fluid to a downstream portion of the aftmost labyrinth tooth and further configured to generate an aerodynamic force between the shoe plate and the rotor. Each of the segments also includes a secondary seal configured to be in contact with the stator interface element at a radially outer end and configured to be in contact with an elevated nose of the shoe plate on a radially inner end and multiple bellow springs or flexures connected to the shoe plate and to the stator interface element.

DRAWINGS

These and other features, aspects, and advantages of the present invention will become better understood when the following detailed description is read with reference to the accompanying drawings in which like characters represent like parts throughout the drawings, wherein:

FIG. **1** is a perspective view of a film riding seal assembly of a rotary machine in accordance with an embodiment of the present invention.

FIG. **2** is a perspective view of a sealing device segment in accordance with an embodiment of the present invention.

FIG. **3** is a perspective view of adjacent sealing device segments of a film riding seal assembly of a rotary machine in accordance with an embodiment of the present invention.

FIG. **4** is a perspective view of a sealing device segment in accordance with another embodiment of the present invention.

FIG. **5** is a front perspective view of a portion of a sealing device segment in accordance with an embodiment of the present invention.

FIG. **6** is a perspective view of a sealing device segment in accordance with another embodiment of the present invention.

FIG. **7** is a perspective view of a sealing device segment in accordance with yet another embodiment of the present invention

FIG. **8** is a portion of a sealing device segment in accordance with one embodiment of the present invention.

FIG. **9** is a portion of a sealing device segment in accordance with another embodiment of the present invention.

FIG. **10** is a side view of the sealing device segment showing various pressure forces acting on the shoe plate and the secondary seal in accordance with an embodiment of the present invention.

FIG. **11** is a cross-section view at center of the sealing device segment **17** in accordance with an embodiment of the present invention.

FIG. **12** shows a shoe-rotor curvature in the seal assembly in accordance with an embodiment of the present invention.

FIG. **13** shows grooves on a load-bearing surface in a sealing device segment in accordance with an embodiment of the present invention.

FIG. **14** shows a rotor-stator seal assembly in accordance with an embodiment of the present invention.

FIG. **15** shows a portion of the sealing device segment in accordance with an embodiment of the present invention.

FIG. **16** is flow chart illustrating steps involved in method of manufacturing a sealing device segment in accordance with an embodiment of the present invention.

DETAILED DESCRIPTION

When introducing elements of various embodiments of the present invention, the articles "a," "an," "the," and "said" are intended to mean that there are one or more of the elements. The terms "comprising," "including," and "having" are intended to be inclusive and mean that there may be additional elements other than the listed elements. Any examples of operating parameters are not exclusive of other parameters of the disclosed embodiments.

FIG. **1** is a perspective view of a film riding seal assembly **10** (only a few segments are shown instead of the entire 360 degree assembly) for a rotary machine in accordance with an embodiment of the present invention. The film riding seal assembly **10** is shown to have an orientation in axial, radial and circumferential direction as given by **11**, **13** and **15** respectively. The seal assembly **10** is circumferentially arranged around a rotor shaft (not shown) that is axially located in the rotary machine such that the seal assembly **10** is intermediate to a stationary housing **12** and the rotor shaft (not shown). The stationary housing **12** includes multiple stator interface elements **14** that form the radially outwards region of the seal assembly **10**. The seal assembly **10** includes multiple sealing device segments **16** located adjacent to each other to form the seal assembly **10**. Each of the sealing device segment **16** includes a shoe plate **18** located proximate to the rotor shaft (not shown). During operation of the rotary machine, the shoe plate **18** rides on a fluid film above the rotor shaft (not shown). The seal assembly **10** also includes one or more labyrinth teeth **20** located on the shoe plate **18** at a side facing the rotor shaft surface. In one embodiment as shown, the one or more labyrinth teeth **20** are located towards forward-most region of the shoe plate **18**. In another embodiment, the one or more labyrinth teeth **20** are located towards an aftmost region of the shoe plate **18**. The one or more labyrinth teeth **20** substantially separate a high pressure region **22** from a low pressure region **24** on either sides of the seal assembly **10** of the rotary machine. The seal assembly **10** also includes multiple secondary seals **26** configured to be in contact with the stator interface elements **14** at a radially outer end and configured to be in contact with the shoe plate **18** on a radially inner end. In one embodiment, the secondary seal **26** includes an outer layer section **28** (shown in FIG. **2**) and an inner layer section **30** (shown in FIG. **2**) such that each of the outer layer section **28** of the secondary seal **26** overlaps the sealing device segment gaps formed between inner layer sections **30** of adjacent secondary seal segments **16**.

FIG. **2** is a perspective view of the sealing device segment **16** in accordance with an embodiment of the present invention. As shown, the sealing device segment **16** includes stator interface element **14** and the shoe plate **18**. In the embodiment as shown, the shoe plate **18** includes the one or more labyrinth teeth **20** facing the rotor and a load-bearing surface region **32**. The shoe plate **18** is configured to allow a high pressure fluid to an upstream portion **34** of forwardmost labyrinth tooth **20** and a low pressure fluid to a downstream portion **36** of the aftmost labyrinth tooth **20** and further configured to generate an aerodynamic force between the shoe plate **18** and the rotor. The sealing device segment **16** also includes multiple bellow springs **38**, **40** attached to the shoe plate **18** and the stator interface element **14**. In one embodiment, the sealing device segment **16** includes multiple flexures attached to the shoe plate **18** and the stator interface element **14** instead of the multiple bellow springs.

As shown, the shoe plate **18** includes one or more ports **19** located axially downstream of the one or more labyrinth teeth **20** for allowing flow of low pressure fluid from the downstream portion **36** of aftmost labyrinth tooth **20** to the rear cavity **42**. In one embodiment, the one or more ports **19** are angled for allowing flow of the low pressure fluid in a radial direction from behind the labyrinth teeth **20** into a rear cavity **42** formed by the plurality of bellow springs **38**, **40** or flexures, the stator interface element **14** and the shoe plate **18**. In another embodiment, the one or more ports **19** are angled for allowing flow of the low pressure fluid in a circumferential direction causing the fluid to swirl as the fluid transfers from behind the labyrinth teeth to radially above the shoe plate **18**. The swirl causes the fluid to gain tangential velocity in a direction of rotation of the rotor or opposite to the direction of rotation of the rotor. The shoe plate **18** also includes feeding grooves **44** oriented axially on both sides of the load-bearing surface region **32** of the shoe plate **18**. The one or more ports **19** on the shoe plate **18** located axially downstream of the labyrinth teeth **20** along with the feeding grooves **44** ensure that low pressure fluid is present downstream of the labyrinth teeth **20**.

Further as shown, the sealing device segment **16** also includes the secondary seal **26** with the outer layer section **28** and an inner layer section **30**. In one embodiment, the inner layer section **30** is attached via welding or brazing with the stator interface element **14** at a radially outer end. The outer layer section **28** of the secondary seal **26** includes an overhanging portion that overlaps the segment gaps between the inner layer sections **30** of neighboring sealing device segments **16**. The details of the outer layer section **28** of the secondary seal **26** are illustrated further in FIG. **3**, which shows adjacent sealing device segments **16** of the film riding seal assembly **10**.

As shown in FIG. **3**, a portion of the outer layer section **28** of the secondary seal **26** is attached with the stator interface element or the inner layer section **30** via welding or brazing at the radially outer end. The remaining overhanging portion of the outer layer section **28** overlaps the segment gaps between the inner layer sections **30** of neighboring sealing device segments **16**. The overhanging portion of the outer layer **28** extends beyond the single sealing device segment **16** and is ship lapped with the inner layer section **30** of adjacent sealing device segment **16**. Further, the outer layer **28** is free to slide over the inner layer sections **30** of neighboring sealing device segments **16**. As shown in FIG. **3**, only the inner layer section **30** of the secondary seal **26** is configured to be in a line contact with an elevated nose **48** of the shoe plate **18** on the radially inner side.

Furthermore in the embodiments shown in FIG. **2** and FIG. **3**, the stator interface element **14** includes one or more grooves or slots **50** at sides for allowing disposal of spline seal shims **51** for reducing segment-gap leakage between stator interface elements **14** of neighboring sealing device segments

16. Similarly, the shoe plate might include grooves or slots **52** for allowing disposal of spline seal shims for reducing segment-gap leakages between shoe plates **18** of neighboring sealing device segments **16**.

FIG. **4** shows another perspective view of the sealing device segment **16** in accordance with an embodiment of the present invention. In one embodiment as shown, the shoe plate **18** also includes one or more axial rib sections **46**. The one or more axial rib sections **46** are used to increase the flexural stiffness of the shoe plate **18** against aerodynamic and aerostatic loads during operation of the rotary machine.

FIG. **5** is a front perspective view of a portion of a sealing device segment in accordance with an embodiment of the present invention. It is to be noted that the secondary seal **26** has not been shown for the purpose of illustrating a flat region **60** of the stator interface element where the radially outer end of the inner layer section **30** (shown in FIG. **2** and FIG. **3**) of the secondary seal **26** (shown in FIG. **2**, FIG. **3** and FIG. **4**) is attached via brazing or welding.

FIG. **6** is a perspective view of a sealing device segment **17** in accordance with another embodiment of the present invention. As shown, the shoe plate **18** includes a L-shaped structure **70** with an elevated nose section **72** for contact with the inner layer section **30** of the secondary seal **26**. The L-shaped structure includes one or more labyrinth teeth **20** located towards a front end of the shoe plate **18** for separating the high pressure side **22** from the low pressure side **24**. In this embodiment, the L-shaped structure includes one or more ports **74** for allowing flow of low pressure fluid from the downstream portion of aftmost labyrinth tooth **20** to the rear cavity **42**.

FIG. **7** is a perspective view of a sealing device segment **21** in accordance with yet another embodiment of the present invention. In this embodiment, the shoe plate **18** includes a L-shaped structure **71** with an elevated nose section **73** for contact with the inner layer section **30** of the secondary seal **26**. The L-shaped structure includes one or more labyrinth teeth **31** located towards a backward end of the shoe plate **18** for separating a high pressure side from a low pressure side and one or more ports **27** for allowing flow of high pressure fluid from a front cavity **33** formed by the plurality of bellow springs **38**, **40** or flexures, the stator interface element **14** and the shoe plate **18** to an upstream portion of frontmost labyrinth tooth **31**. In one embodiment, the one or more ports **27** are angled for allowing flow of the high pressure fluid in a radial direction from the front cavity **33** to the upstream portion of the forwardmost labyrinth tooth **31**. In another embodiment, the one or more ports **27** are angled for allowing flow of the high pressure fluid in a circumferential direction causing the fluid to swirl as the fluid transfers from the front cavity **33** to the upstream portion of the forwardmost labyrinth tooth **31**.

FIG. **8** shows a portion of a sealing device segment **23** in accordance with one embodiment of the present invention. The secondary seal **26** with the outer layer section **28** and the inner layer section **30** is attached to the stator interface element **14** such that the secondary seal **26** is tilted with respect to a direction perpendicular to an axial direction of the rotary machine to include an optimum angle 'a'. This optimum angle 'a' is included for attaining an almost constant magnitude of contact force for compensating the reduced contact force caused in the event of reduction in effective length of the pressure-loaded portion of the secondary seal **26**.

FIG. **9** shows a portion of a sealing device segment **25** in accordance with one embodiment of the present invention. As shown, in this embodiment, the secondary seal **26** includes an outer layer section **80** and an inner layer section **82** with a slanted profile for maintaining an almost constant force between the secondary seal **26** and the elevated nose **48** of the shoe plate **18** at the line contact during radial motion of the shoe plate **18**.

FIG. **10** is a side view of the sealing device segment **16** that shows various pressure forces acting on the shoe plate **18** and the secondary seal **26** in accordance with an embodiment of the present invention. In a non-limiting example, the shoe plate **18** may ride on a fluid film in an aerostatic mode of operation, where the fluid film thickness may range from about 3/1000 inches to 5/1000 inches depending on an initial seal assembly clearance with the rotor. In the aerostatic mode of operation, the forces acting on the shoe plate **18** are an axial force N due to contact force from secondary seal **26**, wherein the secondary seal **26** is subjected to pressure force P_{high} on forward side and pressure force P_{low} on aft side during pressurization, a friction force μN due to contact force from the secondary seal **26**, a small radial opening force on the shoe plate **18** due to unequal pressures force P_{low}, P_{high}, respectively above and below the elevated nose **48**, and an axial force caused by the unequal pressures on the radially vertical faces of the shoe plate **18**. It is to be noted that the load-bearing surface region **32** is subjected to a pressure force P_{shoe} and the shoe face on the inner cavity side is subjected to the pressure force P_{low}. Upon pressurization and in the absence of rotation, since majority of the axial pressure drop occurs across the labyrinth tooth **20**, the pressure P_{shoe} is almost equal to P_{low}. In this aerostatic sense, the shoe plate **18** is inherently pressure balanced in radial direction for most of the shoe length leaving only a very small opening force caused by the unbalanced radial force across the elevated nose **48**. Such a pressure-balanced seal is advantageous for both low and high-pressure applications, where the pressurization will not cause the seal to open and leak excessively. It is to be noted that the sealing device segment **17** as shown in FIG. **6** may include similar pressure forces acting on the shoe plate **18** and the secondary seal **26** as discussed with respect to the sealing device segment **16**. However, it is to be further noted that for the embodiment **21** shown in FIG. **7**, the above discussion is equally valid except that the pressure force within the front cavity **33** is P_{high} and the pressure force P_{shoe} is almost equal to P_{high}. Furthermore, in these various embodiments as shown in FIG. **2**, FIG. **6** and FIG. **7**, the moment-balance is addressed with the zero-tilt design explained below and the effects of rotor speed are addressed in the aerodynamic mode of operation.

In this embodiment as shown in FIG. **10**, the position of the contact between the secondary seal **26** and the stator interface element **14** at the radially outer end, the position of the contact between the inner layer section **30** of the secondary seal **26** with the shoe plate **18** at the radially inner end (i.e. the location of the elevated nose); and the attachment location of the plurality of bellow springs **38**, **40** or flexures to the shoe plate **18** and to the stator interface element **14** at predetermined positions are based on a relative position of a line of action of an effective axial force F, acting on the plurality of bellow springs or flexures for attaining a zero or small front-aft tilt of the shoe plate. The position of line of action of effective axial force F acting on the plurality of bellow springs or flexures is defined as the sum of moments caused due to all the applied forces on the shoe (moments calculated about the point located at the axial midspan of the bellow springs **38**, **40** or flexures where the bellow springs **38**, **40** or flexures connect with the shoe plate **18**) divided by the total axial force acting on the shoe plate **18**. It is to be noted that a zero-tilt causes the shoe plate to remain parallel to the rotor before, after and during pressurization of the rotary machine. This zero-tilt of the shoe plate **18** is achieved when the line of action of the effective axial force F acts on a midpoint (radial direction) of the bellow springs **38**, **40** or flexures. As shown in this embodiment, the relative position of the effective axial force F is the midpoint M, wherein M is half of a length measured radially from the attachment of the plurality of bellow springs **38**, **40** or flexures with the shoe plate **18** to attachment of the plurality of bellow springs **38**, **40** or flexures with the stator interface element **14**. During manufacturing, the line of action of the effective axial force F is ensured to pass through the midpoint M by adjusting one or more of the dimensions of the shoe plate **18** (thickness or location of elevated nose **48** or radius of elevated nose **48**), dimensions and material properties of the secondary seal **26** (length, thickness, tilt angle/profile), dimensions and material of the plurality of bellows springs or flexures (radial height, thickness), friction properties of the secondary seal **26** and the shoe plate **18**. It is to be noted that the shoe plate **18** may ride on a fluid film in an aerodynamic mode of operation, where the fluid film thickness may range from about 0.3/1000 inches to 3/1000 inches depending on an initial seal assembly clearance with the rotor. The discussion above for force balance and zero-tilt aerostatic mode is equally valid for aerodynamic mode except that the pressures P_{shoe} are different (higher) in the case of aerodynamic mode compared to the aerostatic mode due to the shoe design features described later. The additional pressure P_{shoe} is balanced by a radial spring force caused due to the compression of the bellow springs or flexures.

FIG. **11** is a cross-section view at center of the sealing device segment **17** in accordance with an embodiment of the present invention. As shown, the shoe plate **18** includes one or more pressurization ports **90** located axially for allowing flow of the high pressure fluid to a rotor-shoe gap. This high pressure fluid causes a small opening force that moves the shoe plate **18** radially outwards by about 1/1000 inch to 2/1000 inch. This initial lift or opening is important for sealing device segments that are assembled line-on-line with the rotor or assembled with an interference with the rotor. The one or more pressurization ports **90** provide the advantage for assembling the sealing device segments **17** closer to the rotor. The one or more pressurization ports **90** help avoid start-up rubs by providing an aerostatic pressure distribution between the rotor and the shoe plate, thereby lifting the shoe plate **18** away from the rotor during the initial rotation start-up phase when the aerodynamic force is not large enough to avoid shoe plate-rotor contact. The axial location of the port **90** is suitably chosen such that the aerostatic pressure distribution causes a uniform shoe plate lift-off without any front-aft tilting of the shoe. In another embodiment, a flexible tube (not shown in FIG. **11**) is routed suitably to carry high pressure fluid to the load-bearing surface. The flexibility of the tube is designed to allow for radial motion of the shoe plate **18** without any additional radial stiffness caused by the tube connection.

FIG. **12** shows a shoe-rotor curvature in the seal assembly **10** in accordance with an embodiment of the present invention. The seal assembly **10** also operates in an aerodynamic mode of operation. When the rotor-shoe plate gap starts reducing (e.g. during a thermal transient event causing clearance change), a thin fluid film **100** starts building additional pressure. In this embodiment, the radius of curvature of the shoe plate **18** is intentionally machined to be larger than the rotor radius. As a consequence, when the rotor-shoe plate gap becomes small (typically less than 1/1000 inch), the fluid film **100** is either monotonically converging or converging-diverging in the direction of rotation. This fluid film in a form of fluid wedge causes additional pressure to build-up. The physics of thin film is well understood from hydrodynamic journal bearings or foil bearings, and can be modeled using appropriate fluid flow models. The basic principle is that any negative gradient in the fluid film thickness in the direction of rotation will increase the pressure in the fluid film above its boundary pressure. The additional pressure caused by the thin fluid film squeezes the bellow springs **38**, **40** thereby, moving the shoe plate **18** radially outwards and keeping the rotor **92** from contacting the shoe plate **18**. In this sense, any outward excursion of the rotor **92** is tracked by the shoe plate **18** on every sealing device segment **16**, **17**, **23**, **25**.

In another embodiment as shown in FIG. **13**, the thin fluid film generates additional aerodynamic force due to the presence of grooves **110** or pockets (not shown in FIG. **13**) on the load-bearing surface region **32** facing the rotor. The grooves **110** or pockets are in the form of a series of wedges that causes formation of a convergent fluid film in the direction of rotation. The grooves **110** or pockets can be aligned at an angle relative to the axial direction. In yet another embodiment, the load-bearing surface region **32** includes one or more Rayleigh steps facing the rotor for generating the aerodynamic force.

FIG. **14** shows a rotor-stator seal assembly **120** in accordance with an embodiment of the present invention. In one embodiment, the rotor-stator seal assembly **120** includes slots **122** in a herringbone pattern on the rotor **92** for generating aerodynamic forces during operation of the turbo-machinery. The herringbone pattern on the rotor **92** could be in the direction of rotation or opposite to the direction of rotation. In another embodiment, the rotor **92** includes grooves or pockets or slots that are in either axial or angled in a combined axial-tangential direction (these angles slots grooves or pockets are not shown in FIG. **14**). Further, the slots or grooves or pockets on the rotor **92** are aligned in the direction of rotation or opposite to the direction of rotation.

FIG. **15** shows a cross-section view for a portion of the sealing device segment **16** where the labyrinth teeth **20** are located at a radial height ‘h’ away from the load-bearing surface **32**. This results in the labyrinth tooth **20** running at a larger clearance from the rotor than the clearance between the load-bearing portion and the rotor. This difference in radial clearance allows for accommodation of a bi-directional tilt correction. During operation of the rotary machine, the load-bearing surface region **32** is intended to ride almost parallel to the rotor along the axial direction. However due to assembly mismatch or unexpected thermal or pressure loading, the load-bearing surface region **32** tilts so that either the forward or the aft edge of the load-bearing surface region **32** is closer to the rotor. If the aft edge is closer to the rotor, riding gap between the aft edge and the rotor is smaller than the riding gap between the forward edge and the rotor. This leads to larger aerodynamic force generation on the shoe plate **18** near the aft edge, causing a correcting aerodynamic moment on the shoe plate. This aerodynamic moment prevents the shoe plate from rubbing against the rotor on the aft edge. On the other hand, if the load-bearing surface region **32** is tilted such that the forward edge is closer to the rotor and if the dimension ‘h’ (as described above) is zero, then the labyrinth teeth **20** might rub into the rotor because of the insufficient area available to generate aerodynamic moment needed for correcting the shoe plate tilt. However, a non-zero clearance ‘h’ causes the forward edge of the load-bearing surface region **32** to interface with the rotor before the labyrinth teeth **20** rubs against the rotor, thereby allowing the load-bearing portion to generate the needed correcting aerodynamic moment.

In a non-limiting example, both the bellows springs **38**, **40** and the secondary seal **26** (as shown in FIG. **2**) are formed from high temperature metal alloy shims like Inconel X750 or

Rene41. In one embodiment, both ends of the bellow springs **38**, **40** are brazed to the stator interface element **14** and the shoe plate **18**, which are machined or cast. In another embodiment, the bellow springs or flexures are machined using an EDM procedure, which allows machining of the stator interface, the bellows or flexures and the shoe from a single block of metal. In a non-limiting example, the load bearing portion **32** of the shoe plate **18** may be coated with lubricating and/or wear-resistant coating, which comprises of chromium or nickel or molybdenum as the base along with hard phases and solid lubricants. In another non-limiting example, the coating on the load-bearing surface **32** of the shoe plate **18** comprises of cobalt-based alloys. Such coatings can handle unintentional rubs between the shoe plate **18** and the rotor. In another embodiment, the rotor surface interfacing with the shoe plate **18** may be coated with chromium carbide or tungsten carbide or similar coatings to improve the rotor's hardness, corrosion resistance and the ability to maintain a good surface finish.

FIG. **16** is flow chart **200** illustrating steps involved in method of manufacturing a sealing device segment. At step **202**, the method includes disposing a shoe plate comprising one or more labyrinth teeth facing the rotor and a load-bearing surface region intermediate to a stationary housing and a rotor in a rotary machine. The shoe plate is configured to allow a high pressure fluid to an upstream portion of the forwardmost labyrinth tooth and a low pressure fluid to a downstream portion of the aftmost labyrinth tooth and further configured to generate an aerodynamic force between the shoe plate and the rotor. At step **204**, the method also includes arranging a secondary seal to be in contact with a stator interface element at a radially outer end and in contact with an elevated nose of the shoe plate on a radially inner end. Further, at method **206**, the method includes connecting a plurality of bellow springs or flexures to the shoe plate and to the stator interface element. This method includes contacting the secondary seal with the stator interface element at the radially outer end and the elevated nose of the shoe plate at the radially inner end at predetermined positions based on a relative position of a line of action of an effective axial force on the plurality of bellow springs or flexures for attaining a zero or small front-aft tilt of the shoe plate.

Further the method also includes connecting an inner layer section of the secondary seal to the stator interface element and contacting the inner layer section with an elevated nose of the shoe plate. The method also includes overlapping the segment gaps between the inner layer sections of neighboring sealing device segments with an overhanging portion an outer layer section of the secondary seal.

In another embodiment, the method also includes coating on the load-bearing surface region of the shoe plate with a lubricating coating and/or a wear resistant coating. In a non-limiting example, the wear-resistant and lubricating coating on the load-bearing surface **32** of the shoe **18** comprises of chromium or nickel or molybdenum as the base along with hard phases and solid lubricants. In another non-limiting example, the coating on the load-bearing surface **32** of the shoe plate **18** comprises of cobalt-based alloys. Such coatings can handle unintentional rubs between the shoe plate **18** and the rotor. Furthermore, in another embodiment, the method includes coating a rotor surface interfacing the shoe plate with a wear-resistant coating material. In a non-limiting example, the wear-resistant coating material is chosen from a group of chromium carbide or tungsten carbide and the like.

Advantageously, the present aerodynamic seal assemblies are reliable, robust seal for several locations in rotating machinery with large pressure drops and large transients. The seal assemblies are also economical to fabricate. The non-contact operation of the seals makes them especially attractive for the large rotor transient locations. Further, the present invention allows independent controlling of the spring stiffness and the pressure resisting capability, thereby allowing the design of compliant seals that can withstand large differential pressures. Furthermore, the present invention allows for a shoe plate to remain almost parallel to the rotor along the axial direction in aerostatic operation and translate almost parallel to the rotor along the axial direction during the aerodynamic mode. The present invention also includes improved predictability for the radial motion (increased predictability for leakage performance and robustness).

Furthermore, the skilled artisan will recognize the interchangeability of various features from different embodiments. Similarly, the various method steps and features described, as well as other known equivalents for each such methods and feature, can be mixed and matched by one of ordinary skill in this art to construct additional systems and techniques in accordance with principles of this disclosure. Of course, it is to be understood that not necessarily all such objects or advantages described above may be achieved in accordance with any particular embodiment. Thus, for example, those skilled in the art will recognize that the systems and techniques described herein may be embodied or carried out in a manner that achieves or optimizes one advantage or group of advantages as taught herein without necessarily achieving other objects or advantages as may be taught or suggested herein.

While only certain features of the invention have been illustrated and described herein, many modifications and changes will occur to those skilled in the art. It is, therefore, to be understood that the appended claims are intended to cover all such modifications and changes as fall within the true spirit of the invention.

The invention claimed is:

1. A seal assembly for a rotary machine, the seal assembly comprising: a plurality of sealing device segments disposed circumferentially intermediate to a stationary housing and a rotor, wherein each of the plurality of sealing device segments comprises: a stator interface element; a shoe plate comprising one or more labyrinth teeth facing the rotor and a load bearing surface region, wherein the shoe plate is configured to allow a high pressure fluid to an upstream portion of forwardmost labyrinth tooth and a low pressure fluid to a downstream portion of the aftmost labyrinth tooth and further configured to generate an aerodynamic force between the shoe plate and the rotor, a secondary seal configured to be in contact with the stator interface element at a radially outer end and configured to be in contact with an elevated nose of the shoe plate on a radially inner end, wherein the secondary seal comprises an outer layer section and an inner layer section such that each of the outer layer section of the secondary seal having an circumferentially overhanging portion overlaps a sealing device segment gap formed between inner layer section of adjacent secondary seal segments; and a plurality of bellow springs or flexures attached to the shoe plate and to the stator interface element, wherein the shoe plate comprises the one or more labyrinth teeth located towards a front end of the shoe plate for separating a high pressure side from a low pressure side in the rotary machine and one or more ports for allowing flow of low pressure fluid from the downstream portion of aftmost labyrinth tooth to a rear cavity formed by the plurality of bellow springs or flexures, the stator interface element and the shoe plate.

2. The seal assembly of claim 1, wherein the load bearing surface region of the shoe plate comprises one or more grooves or pockets on a side facing the rotor for generating an aerodynamic force.

3. The seal assembly of claim 1, wherein the load bearing surface region of the shoe plate has a radius larger than the rotor radius resulting in a formation of convergent or convergent-divergent fluid film in a tangential direction for generation of an aerodynamic force.

4. The seal assembly of claim 1, wherein the load bearing surface region and the rotor comprises a wear-resistant coating or a layer of lubricating coating on surfaces facing each other.

5. The seal assembly of claim 1, wherein the one or more ports are angled for allowing flow of the low pressure fluid in a radial direction from behind the aftmost labyrinth tooth into the rear cavity formed by the plurality of bellow springs or flexures, the stator interface element and the shoe plate.

6. The seal assembly of claim 1, wherein, the one or more ports are angled for allowing flow of the low pressure fluid in a circumferential direction causing the fluid to swirl as the fluid transfers from behind the aftmost labyrinth tooth to radially above the shoe plate.

7. The seal assembly of claim 1, wherein the shoe plate comprises a L-shaped structure with an elevated nose section for contact with the secondary seal segment.

8. The seal assembly of claim 7, wherein the L-shaped structure comprises one or more labyrinth teeth located towards a front end of the shoe plate for separating a high pressure side from a low pressure side and one or more ports for allowing flow of low pressure fluid from the downstream portion of aftmost labyrinth tooth to a rear cavity formed by the plurality of bellow springs or flexures, the stator interface element and the shoe plate.

9. The seal assembly of claim 7, wherein the L-shaped structure comprises one or more labyrinth teeth located towards a backward end of the shoe plate for separating a high pressure side from a low pressure side and one or more ports for allowing flow of high pressure fluid from a front cavity formed by the plurality of bellow springs or flexures, the stator interface element and the shoe plate to an upstream portion of frontmost labyrinth tooth.

10. The seal assembly of claim 1, wherein the shoe plate comprises one or more axial ribs.

11. The seal assembly of claim 1, wherein each of the sealing device segments comprises feeding grooves oriented axially on both sides of the load-bearing surface region of the shoe plate.

12. The seal assembly of claim 1, where the rotor comprises grooves or slots or pockets rotor angled in axial direction or combined axial and tangential direction or in a herringbone pattern, for generating an aerodynamic force.

13. The seal assembly of claim 12, wherein the grooves or slots or pockets or the herringbone pattern on the rotor are aligned in the direction of rotation or opposite to the direction of rotation.

14. The seal assembly of claim 1, further comprising a labyrinth teeth clearance more than a load bearing surface region clearance.

15. The seal assembly of claim 1, wherein the stator interface element comprises one or more grooves or slots for allowing disposal of one or more spline seal shims for reducing segment-gap leakage between stator interface elements of neighboring sealing device segments.

16. The seal assembly of claim 1, wherein the shoe plate comprises one or more pressurization ports located axially for allowing flow of the high pressure fluid to a rotor-shoe gap.

17. The seal assembly of claim 1, wherein the shoe plate comprises grooves or slots for allowing disposal of spline seal shims for reducing segment-gap leakages between shoe plates of neighboring sealing device segments.

18. The seal assembly of claim 1, wherein a location of the contact between the secondary seal and the stator interface element at the radially outer end, a location of the contact between the secondary seal with the shoe plate at the radially inner end; and an attachment location of the plurality of bellow springs or flexures to the shoe plate and to the stator interface element are at predetermined positions based on ensuring that a line of action of an effective axial force passes through the plurality of bellow springs or flexures at about the radial midspan of the bellow springs or flexures in order to attain a zero or small front-aft tilt of the shoe plate.

19. The seal assembly of claim 1, wherein the secondary seal is tilted with respect to a direction perpendicular to an axial direction of the rotary machine to include an optimum angle for attaining an almost constant magnitude of contact force for compensating the reduced contact force caused by reduction in effective length of the secondary seal.

20. The seal assembly of claim 1, wherein the secondary seal comprises an inner layer section with a slanted profile for maintaining a constant force between the secondary seal segment and the shoe plate at the line contact during radial motion of the shoe plate.

21. A rotary machine, comprising:

a rotor;

a stationary housing; and

a seal assembly according to claim 1.

22. The rotary machine of claim 21, wherein the contact between the secondary seal and the stator interface element at the radially outer end, the contact between the secondary seal with the shoe plate and the radially inner end; and the attachment of the plurality of bellow springs or flexures to the shoe plate and to the stator interface element are at predetermined positions based on ensuring thata line of action of an effective axial force passes through the plurality of bellow springs or flexures at about the radial midspan of the plurality of bellow springs or flexures in order to attain a zero or small front-aft tilt of the shoe plate.

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